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# Oil Absorption Into Cotton-Phenolic Material

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The kinetics of oil absorption into cotton-phenolic ball-bearing retainer material were determined. The results fit a model of two-step absorption in which the first step can be described by capillary rise and the second step by diffusion of oil from the capillaries into the bulk phenolic resin. The capillaries are associated with the cotton threads and are on the order of several $\mu$m or less in radius. The model successfully describes data for two cotton-phenolics with different cloth weaves, and five nonpolar liquids (four lubricating oils and heptane) with viscosities that vary over 3 orders of magnitude. The total amount of oil absorbed at the completion of the first step (1.5 to 3.4% v/v in this work) is proportional to the volume of the sample, not its surface area, suggesting that the entire volume of the material stores oil and not just the surface region. If the material is not completely dry when submerged in oil, the capillaries are blocked and only surface absorption of oil can take place. The saturation amount of oil in the resin after diffusion is complete is about 2 to 3 % v/v (not

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including the amount of oil stored in the capillaries). The diffusion coefficient calculated using our model is $3 \times 10^{-12}$ cm$^2$/s, which is reasonable when compared with available literature data on large and small molecules diffusing into polymers.

# PREFACE

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# I. INTRODUCTION

Cotton-phenolic material is used in the ball retainers, also called cages, of many ball bearings. The material can absorb lubricating oil; in fact, oil is impregnated into the retainers in the hopes that the retainer will function as an oil reservoir (i.e., a resupply system). Oil is absorbed into the material quickly at first, and then more slowly for long periods of time. In engineering practice, the initial filling is accomplished at least in part by vacuum-impregnating the retainer in warm oil. In this process, the retainer is held above a container of warm oil in a chamber that is then evacuated. The retainer is immersed into the oil and allowed to soak for a period of time, varying from a few hours to a few days. The long-term absorption of oil has never been discussed. If ball retainers continue to absorb oil during storage and use, they could be a sink for lubricant instead of a source.[1] This would have a deleterious effect on the operation of lightly lubricated ball bearings with no oil-replenishment scheme, such as those found in many spacecraft.

The mechanism of oil absorption into cotton-phenolic material has never been determined. In the work reported here, we have varied the properties of the cotton-phenolic materials and the absorbing fluids, observed the kinetics of the oil-absorption process, and developed a model that describes the experimental data very well. Retainer-grade cotton-phenolic material was used in the experiments; actual machined retainers were also studied in concurrent experiments, but the results of those experiments are not reported here. The mechanism of oil absorption is the same for pieces of material and retainers, but the data analysis is much less complicated for the pieces due to their simple shapes (see below).

The model we have developed to describe oil absorption into cotton-phenolic material is based on the anisotropic and composite nature of the material. Cotton-phenolic material is manufactured as tubes by winding cotton cloth impregnated with resin precursors on a mandrel, followed by curing at elevated temperatures. The rates and quantities of oil absorbed are dependent on the specific location within a tube and material handling procedures. The material is a composite (resin plus cloth) and structurally anisotropic (due to the thread directions). The experiments described below show that oil is absorbed into the material by a two-step mechanism: first, oil is absorbed by capillary action into voids associated with the fibers within the cotton threads; then a slow diffusion of oil into the bulk phenolic resin takes place.

## II. EXPERIMENTAL

### A. COTTON-PHENOLIC MATERIALS

Two different cotton-phenolic materials were used in the experiments; they were manufactured with cotton cloths of different weaves. Westinghouse 97, produced by Westinghouse Electric Corp., is made with a 4-oz/yd cloth ($26 \times 26$ to $35 \times 35$ thread matrix on $1 \text{ cm}^2$ of cloth). Spaulding FBEFW, produced by the Spaulding Composites Company, is made with a 3-oz/yd cioth (approximately $35 \times 40$ matrix on $1 \text{ cm}^2$ of cloth). The weight of the cloth in the Spaulding FBEFW is less than that in Westinghouse 97 because even though there are more threads, each thread is finer. The threads are bundles of about 100 cotton fibers twisted together. Each fiber has an oval cross section, about $5 \times 25$ μm, and the spaces between the fibers in a thread are comparable in size to the fibers themselves, with a typical linear dimension of 0 to 50 μm. The fibers and any spaces surrounding them that are not filled by cured resin have been thought of traditionally as "wicks" that draw oil into the material.

The materials were received as cylindrical sections as shown in Fig. 1. The warp threads of the cloth lie parallel to the axis of the cylinder; the weft threads are wound around the cylinder. Figure 2 shows



SPAULDING FBEFW

$d_1 = 3.810$ cm
$d_2 = 5.032$ cm
h  $= 1.615$ cm
w  $= 0.611$ cm
($c_1$ and $c_2$ are variable)

WESTINGHOUSE 97

$d_1 = 3.368$ cm
$d_2 = 5.390$ cm
h  $= 1.219$ cm
w  $= 1.011$ cm
($c_1$ and $c_2$ are variable)
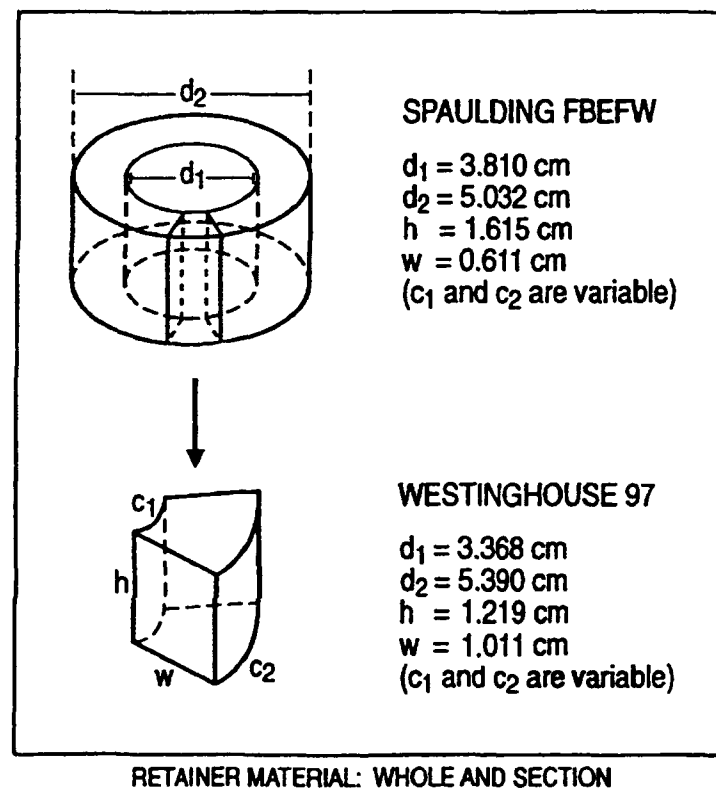
RETAINER MATERIAL: WHOLE AND SECTION

Figure 1. Cotton-phenolic ball-bearing retainer material, as received and sectioned.
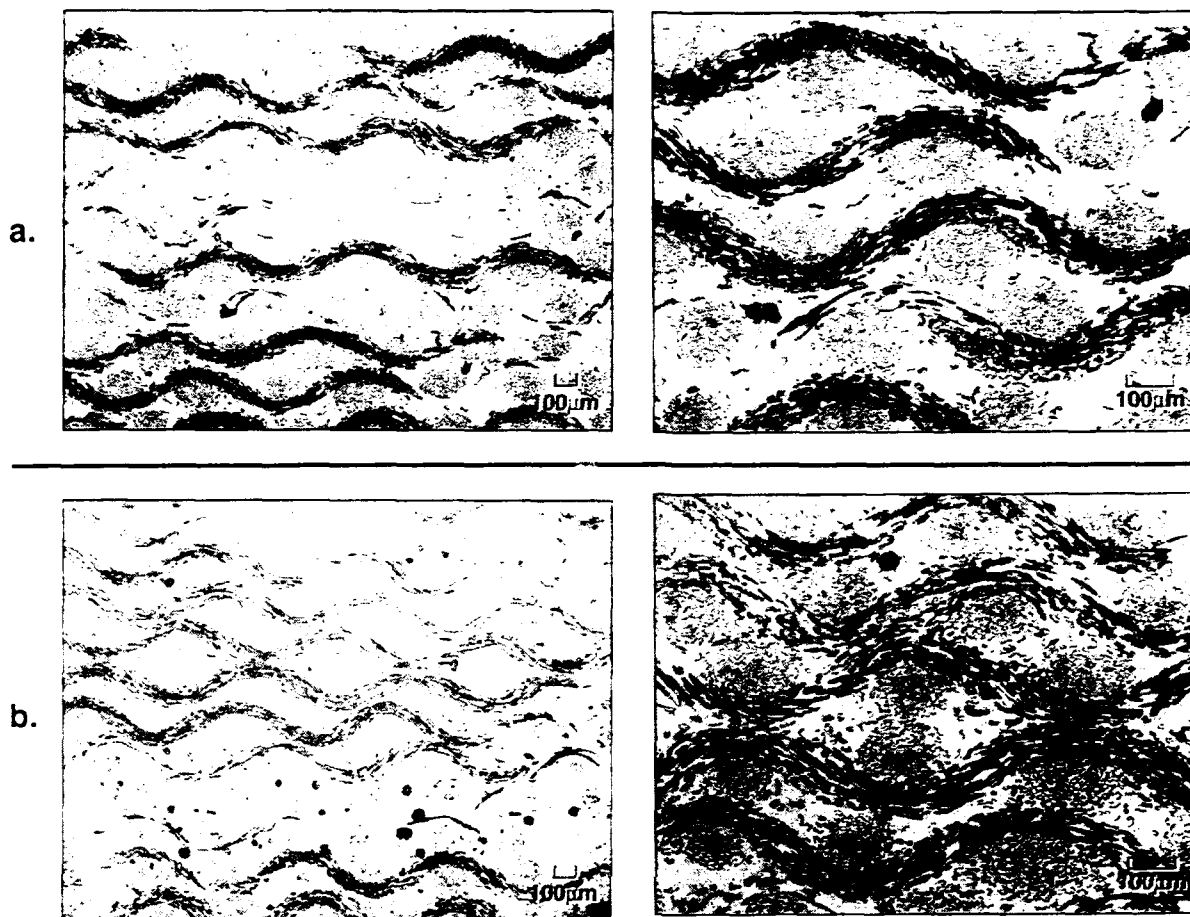
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Figure 2. Photomicrographs of the cotton-phenolic materials, cross-sectioned to view the surface bounded by h and w in Fig. 1. (a) Westinghouse 97: 50X and 100X; (b) Spaulding FBEFW: 50X and 100X.

photomicrographs of the two materials. The surface photographed is that bounded by h and w in Fig. 1. The warp threads are seen as wavy lines across the photomicrographs; the weft threads are viewed end-on. The densities were determined by weighing the tubes as received and dividing the weight by the tube volume. The densities are 1.251 g/cm$^3$ for Westinghouse 97 and 1.238 g/cm$^3$ for Spaulding FBEFW. The density of the composite is affected by the weave and density of the cotton cloth and also by the cure of the resin. Some low-density resins contain many bubbles that developed during cure. These bubbles are possible sites for oil storage. Many bubbles can be observed in the photomicrographs of the Spaulding material, while only a few can be seen in the Westinghouse material. The surfaces displayed in these photomicrographs were selected at random and are not necessarily typical of the entire sample as regards bubble distribution. However, more bubbles could be a contributing factor in the lower density of the Spaulding material. When converting sample weights to volumes, the weights measured before sample cleaning and drying were used, since this was the state of the phenolic tubes when the densities were determined.

## B. LUBRICATING OILS

Four oils were used in these experiments. They and their selected properties are listed in Table 1. Coray 100 is a petroleum-based, naphthenic oil produced by Exxon. Nye 176H is a synthetic hydrocarbon (poly-α-olefin) fluid formulated by William F. Nye, Inc. Pennzane SHF X2000 is a multiply alkylated cyclopentane synthetic hydrocarbon produced by Pennzoil Products Co. Krytox 143AB is a perfluoropolyalkylether produced by E. I. Du Pont de Nemours & Co., Inc. The solvent used for cleaning the cotton-phenolic material, and as the absorbate in several of the kinetic experiments, was HPLC-grade heptane. Those properties of heptane relevant to the experiments are also listed in Table 1.

## C. EXPERIMENTAL PROCEDURE

Small sections of cotton-phenolic material were sawed out of the tubes as shown in Fig. 1, weighed, Soxhlet-extracted overnight in heptane, baked overnight in vacuum at 110°C, and weighed again quickly in the presence of a desiccant. Cotton-phenolic material absorbs water very quickly, and as will be discussed below, water absorption interferes with oil absorption.

Most of the samples were immersed in containers of oil or heptane immediately after weighing. Several samples were exposed to laboratory air for about two months to allow equilibration with atmospheric humidity (this length of time was determined to be sufficient by other experiments) before being placed in the oil baths. The oil- or heptane-filled containers were kept at room temperature in desiccators for the duration of the experiment. Periodically the samples were removed, centrifuged at 680 G to remove excess oil, weighed, and returned to their baths. The experiments were continued until some of the samples were saturated with oil. The samples from the heptane bath were removed and weighed quickly without centrifuging to avoid excessive evaporation of the volatile absorbate.

Table 1.  Selected Fluid Properties (25°C)

|  | η (poise) | ρ (g/cm$^3$) | γ (dyne-cm) |
|---|---|---|---|
| Coray 100 | 3.67 | 0.9176 | ≈20 |
| Nye 176H | 10.2 | 0.85 | ≈20 |
| Krytox 143AB | 3.78 | 1.89 | 18.5 |
| Pennzane SHF X2000 | 2.21 | 0.85 | ≈20 |
| heptane | 0.00386 | 0.684 | ≈20 |

## III. RESULTS

The results of some of the experiments are shown in Figs. 3 through 5. The ordinate is the actual weight increase in the samples after baking. The different symbols correspond to different test samples. The vertical displacements of the data for the various samples in any one figure are due to the fact that all the samples have slightly different sizes and weights initially, and the data presented in the figures are not normalized. In the discussion below, the data will be broken down for analysis, and appropriate normalizations will be chosen.
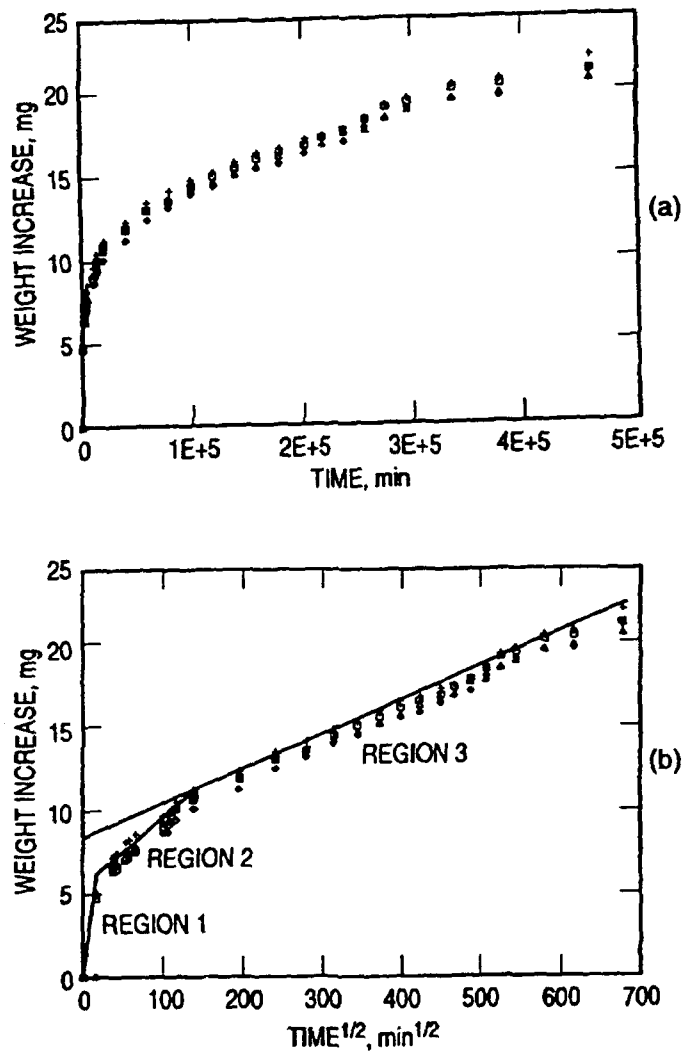


Figure 3. Coray 100 absorption into Westinghouse 97 cotton-phenolic. The different symbols correspond to different test samples. (a) Unnormalized weight increase vs. time. (b) Unnormalized weight increase vs. square root of time.
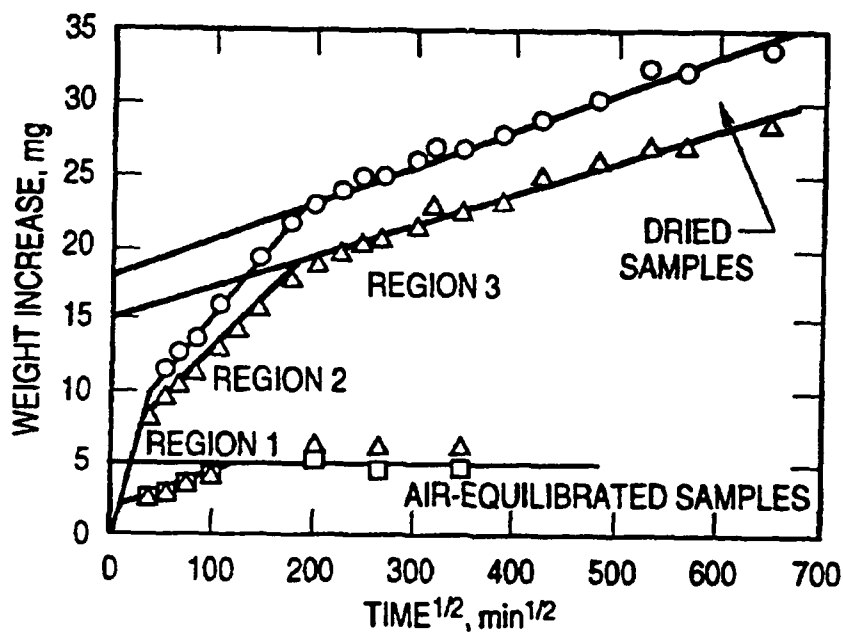
Figure 4. Coray 100 absorption into Spaulding FBEFW cotton-phenolic; unnormalized weight increase vs. square root of time. The different symbols correspond to different test samples.
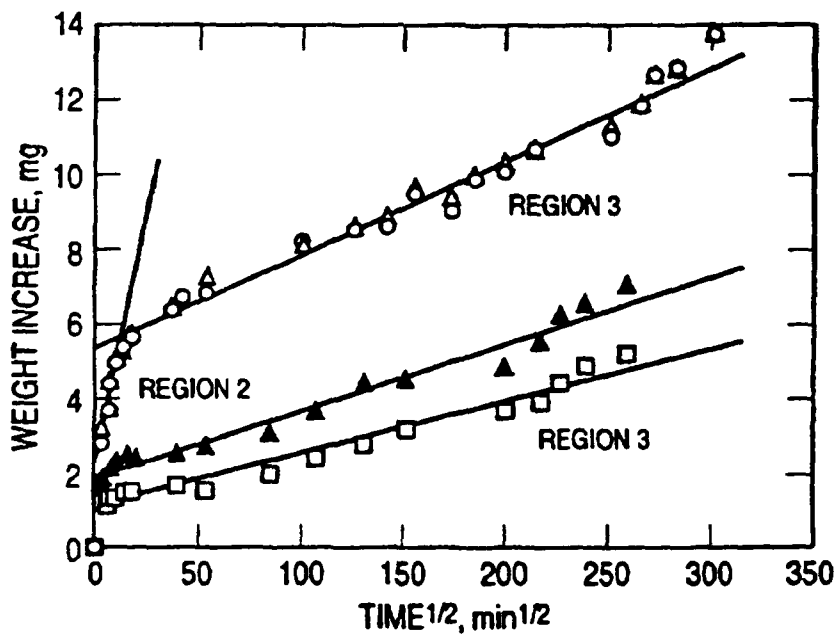


Figure 5. Heptane absorption into Westinghouse 97 cotton-phenolic; unnormalized weight increase vs. square root of time.

The absorption of oil into extracted pieces of cotton-phenolic material starts quickly and then slows down. Heptane absorption follows the same trend as oil absorption. The data for each sample can be divided into two or three sections in which the weight increase is proportional to the square root of time spent in the fluid bath (see Fig. 3b and Fig. 4).

Since the process described by Region 3 is very slow compared to those of Regions 1 and 2, the weight increase due to it can be easily removed in a first approximation. The intercept of the line describing Region 3 with t = 0 can be taken as the amount of weight increase due solely to the processes described in Regions 1 and 2, and the slopes of the lines describing these regions can be considered to be unaffected by the process described in Region 3.

# IV. MODEL AND DISCUSSION

Our model of the absorption process assumes that absorption proceeds by a two-step mechanism. In the first step, oil is wicked up into capillaries within the yarn. This process saturates and stops when the capillaries are filled. In the second step (which is actually concurrent with the first but so much slower that it can be treated as subsequent), oil diffuses from these capillaries as well as through the external surface of the samples into the bulk resin. Heptane absorption proceeds by the same mechanism. (Water absorption is not addressed by this work; water is a polar molecule and may absorb via a different mechanism.)

## A. FIRST STEP — CAPILLARY RISE

The rate of fluid rise in a capillary can be approximated by[2]

$$h(t) = \sqrt{\frac{\gamma r t}{2\eta}} , \tag{1}$$

where $h(t)$ is the height filled at a time $t$, $\gamma$ is the surface tension of the fluid, $r$ is the radius of the capillary, and $\eta$ is the viscosity of the fluid. In the initial calculations, we shall assume the presence of one capillary per thread, and will discuss the extension to multiple capillaries later. The capillaries in adjacent threads are assumed to be unconnected. In our experiments, we measure the weight gain, which is a function of the height and the cross-sectional area of the capillary as well as the density of the fluid ($\rho$). The weight gain as a function of time per capillary is

$$w(t) = \pi r^2 \rho \sqrt{\frac{\gamma r t}{2\eta}} . \tag{2}$$

The only adjustable parameter in this equation is $r$, which must be on the order of $\mu m$ because of the structure of the material, as discussed above.

### 1. Capillary Radius

The samples used in these experiments were all of the same general shape (Fig. 1), but of different sizes. Each sample has warp threads (parallel to $h$ in Fig. 1; 1.2-cm long for Westinghouse 97, and 1.6-cm long for Spaulding FBEFW) and weft threads (parallel to $c_1$ and $c_2$ in Fig. 1; 0.2 to 1.1 cm long). The weft threads were severed during sample preparation. The number of warp threads and weft threads for each sample can be calculated approximately from the size of the sample and the weave of the cloth. In the Westinghouse 97 samples, there are 1440 weft threads (2880 capillary entrances) and from 150 to 580 warp threads (300 to 1160 capillary entrances). In the Spaulding FBEFW samples, there are 1950 weft threads (3900 capillary entrances) and from 370 to 760 warp

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threads (740 to 1520 capillary entrances). These numbers are known to vary ±15% because of the variability in the cloth weave and the tension used to wind the cloth on the mandrel. At first, all the capillaries will be filling, and oil will be adsorbing on the external surfaces (Region 1 in Figs. 2-8), but the capillaries in the weft threads will saturate first because they are shorter. Thus, the capillary-fill region of the process has two different slopes on a weight-gain-vs-$t^{1/2}$ plot: an initial, higher slope (Region 1, warp and weft filling, surface absorption) followed by a lower slope (Region 2, final warp filling). The geometry of actual ball-bearing retainers is very complicated and not amenable to this kind of simple analysis. The mechanism of oil absorption is not easily determined using retainers as experimental samples.

The slopes for oil absorption into the samples, given in units of $cm^3$ of fluid per capillary per $s^{1/2}$, and the calculated r values, given in μm, are listed in Table 2. The values calculated from the data of Region 1 are not as accurate as those calculated from the data of Region 2 since usually there are very few measurements in Region 1, and any quick absorption on the external surfaces also occurs in Region 1. The radii calculated from the Region 1 data will be too large, but are included for completeness. The experiments using heptane as the absorbing fluid are complicated by the high vapor pressure of heptane — heptane evaporates as the samples are being weighed. Weighing was done as quickly as possible to minimize this effect, but the capillary-fill rates reported are necessarily lower than the true capillary-fill rates by the amount of the evaporation rate. Thus, the radius calculated from the heptane data is a lower limit.

The average value of the capillary radius is $3.0 \pm 0.5$ μm. The agreement between all of the r values is very good, and r is of the general size expected due to the structure of the material. In reality, there is probably not one capillary per thread in the material. The capillary rise rate that we measure is the same for one capillary with a 3.0-μm radius as for 10 with 1.2-μm radii. Again, the 1.2-μm radius is also reasonable, based on the structure of the yarn.

## 2. Capillary-Fill Capacity

The amount of liquid stored in this first capillary-fill step can be calculated from the intercept of the Region 3 line as discussed above. It has often been said that oil absorption by cotton-phenolic mate-

Table 2. Capillary-Fill Parameters

| Fluid | Cotton-Phenolic | Region 1 Slope (g/cap. $s^{1/2}$)[*] | r (μm) | Region 2 Slope (g/cap. $s^{1/2}$)[*] | r (μm) | Capillary Fill Capacity (%v/v) |
|---|---|---|---|---|---|---|
| Coray 100 | West. 97 | $9.1 \times 10^{-9}$ | 3.3 | $5.2 \times 10^{-9}$ | 2.6 | 1.6 |
| | Sp.FBEFW | $6.3 \times 10^{-9}$ | 2.8 | $7.0 \times 10^{-9}$ | 3.0 | 2.8 |
| Nye 176H | West. 97 | $8.4 \times 10^{-9}$ | 4.0 | $1.5 \times 10^{-9}$ | 3.0 | 1.7 |
| | Sp.FBEFW | $3.2 \times 10^{-9}$ | 2.7 | $5.2 \times 10^{-9}$ | 3.2 | 3.4 |
| Krytox 143AB | Sp.FBEFW | $1.6 \times 10^{-8}$ | 3.2 | $1.4 \times 10^{-8}$ | 3.0 | 2.9 |
| Pennzane SHF X2000 | West. 97 | $1.1 \times 10^{-8}$ | 3.2 | $6.4 \times 10^{-10}$ | 2.1 | 1.8 |
| heptane | West. 97 | $8.9 \times 10^{-9}$ | 4.1 | $6.0 \times 10^{-10}$ | 2.0 | 1.6 |

[*] Units chosen for slopes are discussed in the text.

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rial is a surface process; the experiments reported here indicate that the amount of oil or heptane stored within the material is dependent on the sample volume, not the surface area. In Fig. 6a, the volume of absorbate contained within each Westinghouse 97 sample is plotted as a function of sample volume; in Fig. 6b, the volume of stored absorbate is plotted as a function of sample surface area.
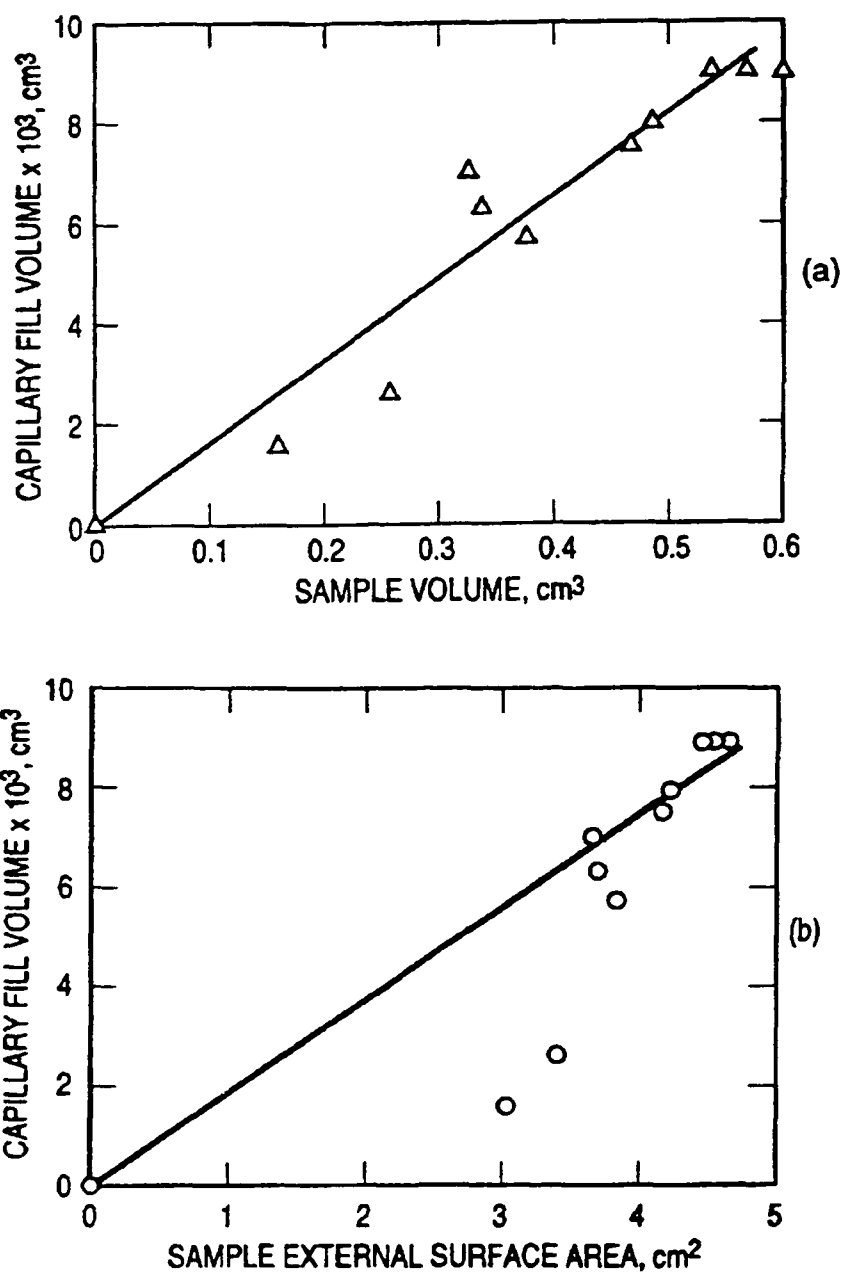


Figure 6. Final volume of liquid absorbed in first step for Westinghouse 97 material, (a) as a function of sample volume; (b) as a function of sample external surface area.

The lines are the best fit of the data (not including the data for the two smallest samples). The two smallest samples were used as a test case. It is clear that the data for the two smallest samples fits the relationship based on volume, but not that based on surface area. Thus, the amount of oil stored depends on sample volume. The rate of absorption depends on the number of capillaries (which is a function of surface area), but the final stored volume of oil depends only on the volume of the cotton-phenolic material.

The capillary-fill capacity is reported as % (v/v) in Table 2. The different materials have different capillary-fill capacities, which are not necessarily correlated with the weave of the cloth. (In fact, in the oil absorption experiments using actual retainers, the capillary fill capacity is definitely not correlated with weave.) In addition, the volume available for oil storage within the $\approx$3-$\mu$m radius capillaries is too small to account for the total amount of oil absorbed by the material in this step.

One possible explanation for this behavior is that the capillary-fill capacity is related to the phenolic resin cure state. There are bubbles within the cotton-phenolic material, presumably the result of gas evolution during cure, that are intersected by the threads. These bubbles could be the major storage volume for oil within the material. The access to the bubbles is regulated by the capillaries (the rate at which the bubbles fill is controlled by the threads), but the volume of oil that can be absorbed is related to the cure of the resin (the number and size of the bubbles). The cure is probably a strong function of the manufacturer because each manufacturer has his own cure recipe, and probably varies from lot to lot. Thus, the Spaulding material could have a different cure state than the Westinghouse material. Of course, this is a very speculative hypothesis.

## 3. Effect of Moisture

Figure 3 shows the absorption data for Spaulding FBEFW filling with Coray 100. The samples that were dry when immersed into oil show much more oil absorption than those that were equilibrated with air. Water vapor, which is present in the air, has absorbed into the cotton-phenolic material and formed a barrier to oil penetration. This illustrates the importance of complete drying of ball-bearing retainers before oil impregnation.

## B. SECOND STEP — DIFFUSION

The second, slow step of the oil absorption process is suggested to be diffusion of the oil into the bulk phenolic resin.

The solution of the diffusion equation for saturation of a plane sheet is

$$\frac{M_t}{M_{sat}} = 1 - \frac{8}{\pi^2} \sum_{m=0}^{\infty} \frac{1}{(2m+1)^2} \exp\left[-D (2m+1^2)\pi^2 \frac{t}{\ell^2}\right], \tag{1}$$

where $M_t$ is the uptake at time t, $M_{sat}$ is the saturation uptake, $2\ell$ is the thickness of the sheet, and D is the diffusion coefficient.[3] Over a limited initial period of time, diffusion processes can be fit to a simple absorption amount vs. $t^{1/2}$ relationship.[3] The diffusion step appears as the linear Region 3 when the data are plotted as a function of the square root of time in Figs. 3 through 5.

The data are used to predict the saturation weight of oil in a particulai 'ece of cotton-phenolic, $M_{sat}$, and this weight is used to normalize the data for that sample. Equatior. ') is then fit to the data, using $D/\ell^2$ as an adjustable parameter. In what follows, this parameter will bt ~ported for each oil/cotton-phenolic combination. The separation of D and $\ell$ will be addressed in m detail below.

## 1. Diffusion-Fill Capacity

The slow diffusion of oil into cotton-phenolic begins to saturate noticeably ai ~ about 1 1/2 years of storage in room-temperature oil baths. The data for Coray 100 absorption into 'estinghouse 97 are plotted in Fig. 7. There are four samples (each sample corresponds to a specific ~mbol in the figure), all about the same dry weight. The data are plotted as weight increase of each sar.ple, unnormalized by either sample dry weight or surface area. Two smooth curves are drawn through the data to illustrate the saturation. Either is a reasonable fit to the data, and both will be used below to assess the precision of the analysis. The projected saturation weights, after subtracting the amount of oil contained within the capillaries, are 17.0 mg and 14.8 mg.

These weights are used as $M_{sat}$ to normalize the data. The results are shown in Fig. 8. Fig. 8a gives the normalized data for $M_{sat} = 14.8$ mg, and Figure 8b gives the normalized data for $M_{sat} = 17.0$ mg. The curves are the best fit of Eq. (3) to the data in each case. The initial few days do not fit very well because during this time the capillaries are filling, and the entire volume of the sample is not penetrated by oil. The capillary-fill capacity has been subtracted from $M_t$ at $t = 0$. Actually, capillary fill and diffusion are occurring simultaneously over the first few weeks.
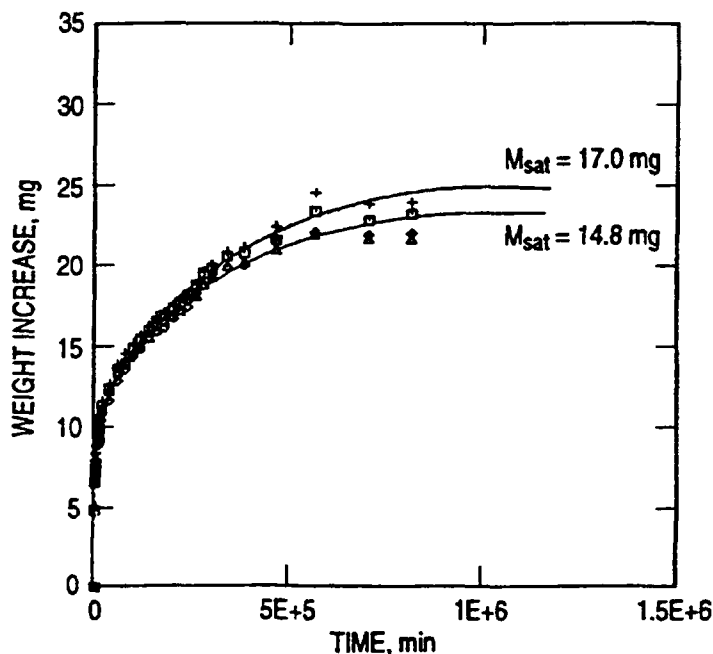


Figure 7. Coray 100 absorption into Westinghouse 97 cotton-phenolic. The different symbols correspond to different test samples. Curves are extrapolations to determine amount of oil in samples at saturation. Both curves fit data equally well.
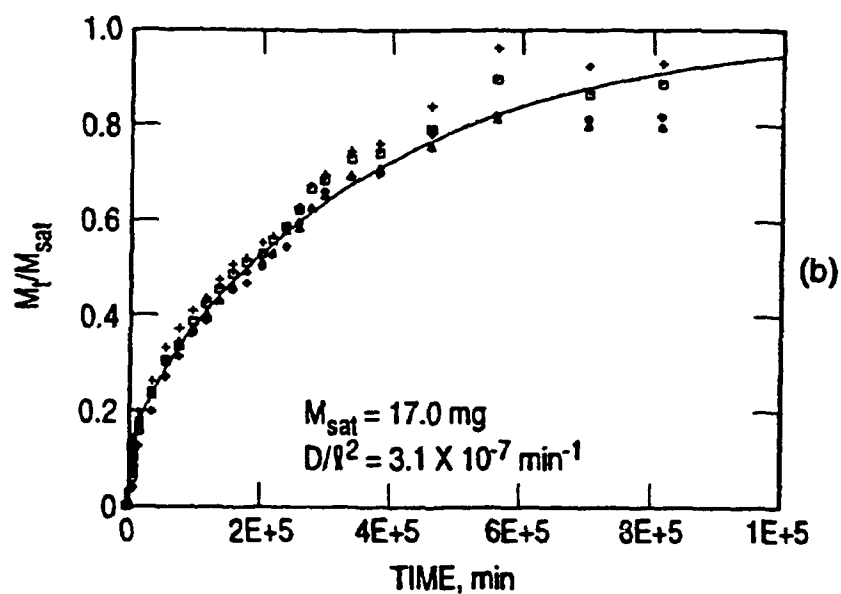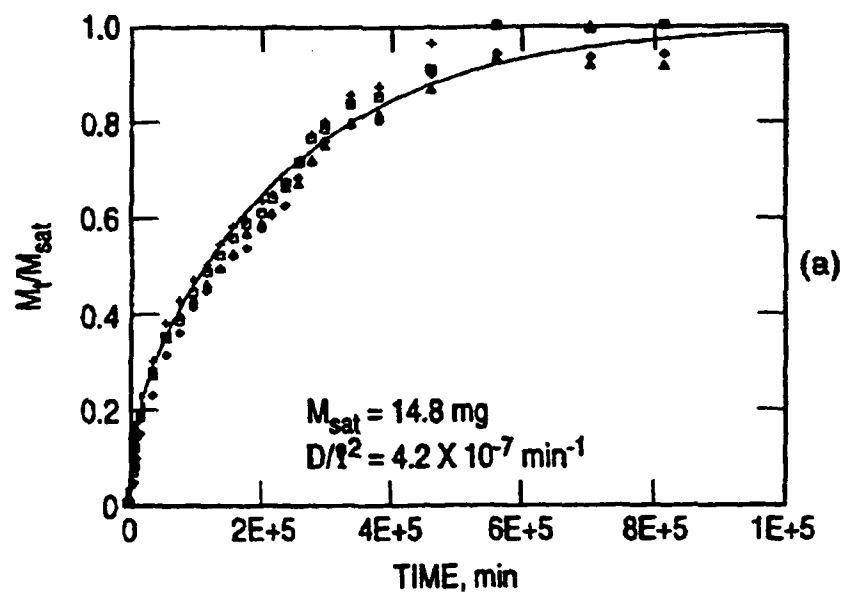
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Figure 8. Long-term diffusion of Cory 100 into Westinghouse 97 cotton-phenolic. The different symbols correspond to different test samples. Curves are best fit to the data. (a) Saturation oil weight of 14.8 mg in the samples. (b) Saturation oil weight of 17.0 mg in the samples.

For $M_{sat}$ = 14.8 mg, $D/\ell^2$ is $4.2 \times 10^{-7}$ min$^{-1}$. For $M_{sat}$ = 17.0 mg, $D/$ is $3.1 \times 10^{-7}$ min$^{-1}$. The calculated values of $D/\ell^2$ are not extremely sensitive to the chosen value $M_{sat}$, so large errors will not be introduced into $D/\ell^2$ when analyzing other experiments in which  s accurate predictions of $M_{sat}$ are possible because the experiments have not run as long. The difi  on-fill capacity is calculated from $M_{sat}$, the oil density, and the volume of the sample, and is 2.7 %  /v for Coray 100 and Westinghouse 97. The results are reported in Table 3.

For Nye 176H absorption into Westinghouse 97 cotton-phenolic (two sample  $M_{sat}$ was predicted to be 6 mg (quite different from the example treated above because the sample s  es are different; refer to Table 3), and the best fit to the data is for $D/\ell^2$ = $6 \times 10^{-7}$ min$^{-1}$. For Cor..v 100 absorption into Spaulding FBEFW (four samples) and Nye 176H absorption into Spaulding FBEFW (four samples), $M_{sat}$, $D/\ell^2$, and the diffusion-fill capacity are given in Table 3.

## 2. Diffusion Coefficient

The values of $D/\ell^2$ obtained from these experiments are the same for all of the oils and all of the cotton-phenolic materials, 4 to $6 \times 10^{-7}$ min$^{-1}$. The diffusion-fill capacities are also about the same, 2 to 3 % v/v. Differences in absorption kinetics discerned in our study of the first capillary-fill step were ascribed to the effects of cloth weave and viscosity of the oil. We do not see any such effects in the second step of the oil absorption process within the accuracy of the experiments.

In order to obtain a value for D, we must know $\ell$. If the solid material were homogeneous, and diffusion were only taking place through the external surfaces, the choice of $\ell$ would be simple: half the width of the sample. For the samples used in this experiment, that would be 0.25 cm (half of the average of $c_1$ and $c_2$, as defined in Fig. 1). Then D could be calculated to be $3 \times 10^{-10}$ cm$^2$/s. This is an unreasonable result; it is much too fast. For comparison, the diffusion coefficient for chloroform, a smaller molecule than the oils used in these experiments, in polystyrene at room temperature[3] is $2 \times 10^{-12}$ cm$^2$/s. The diffusion coefficient for 1,3,5-tris(3,5-di tert-butyl-4-hydroxybenzyl)mesitylene, a much bulkier molecule than the oils, in sheets of isotactic polypropylene at room temperature[4] is $1 \times 10^{-13}$ cm$^2$/s. We would expect D for oils in cotton-phenolic to be in the range of $1 \times 10^{-12}$ to $10^{-13}$ cm$^2$/s.

This calculation results in an unrealistic value for D because cotton-phenolic is not a homogeneous material, and diffusion of oil is taking place through internal surfaces as well as external surfaces. The first step of oil absorption is filling of capillaries and voids associated with the cotton threads.

Table 3. Oil Diffusion into Phenolic Resin

| | Sample Volume (cm$^3$) | $M_{sat}$ (mg) | $D/\ell^2$ (min$^{-1}$) | Diffusion Fill Capacity (% v/v) |
|---|---|---|---|---|
| Westinghouse 97 | | | | |
| Coray 100 | 0.60 | 14.8 | $4 \times 10^{-7}$ | 2.7 |
| Nye 176H | 0.36 | 6.0 | $6 \times 10^{-7}$ | 2.0 |
| Spaulding FBEFW | | | | |
| Coray 100 | 0.64 | 14.1 | $5 \times 10^{-7}$ | 2.4 |
| Nye 176H | 0.37 | 6.2 | $4 \times 10^{-7}$ | 2.0 |

Oil then diffuses out into the bulk phenolic resin from each of the capillaries and voids. The distance over which diffusio 's taking place is the distance between the capillaries, not just the distance between the edges of the samples.

The distance between the capillaries can be approximated by the distance between cotton threads, since the capillaries are associated with the threads. For Westinghouse 97, this distance is 0.048 cm, and for Spaulding FBEFW (with a tighter weave), this distance is 0.036 cm. We can reasonably assume then an $\ell$ of 0.02 cm for both materials. This leads to a diffusion coefficient of $3 \times 10^{-12}$ cm$^2$/s for these oils into phenolic resin. This value is reasonable compared with the literature values for diffusion of organic molecules into polymers, as quoted above.

# IV. CONCLUSIONS

The absorption of five nonpolar liquids with different physical properties in cotton-phenolic ball-bearing retainer material has been measured. We propose a two-step mechanism for the oil absorption process. The oils (and heptane) are initially absorbed into unconnected capillaries in the threads of the cotton cloth; the physical properties of the fluid (density, viscosity, etc.) and the weave of the cloth (number of capillaries per unit surface area) determine the capillary-fill rate. The chemical composition of the liquids used in these experiments does not affect the process, probably because the molecules are all nonpolar and have no specific chemical interactions with either the cotton threads or the phenolic resin. The amount of oil that can be stored in this step is different for cotton-phenolic from different manufacturers, and we speculate that this may be correlated with bubbles within the material due to different cure states.

The long-term absorption of oil into cotton-phenolic material can be modeled as diffusion of oil from capillaries and voids associated with the cotton threads into the bulk phenolic resin. The saturation amount of oil in the resin is about 2 to 3 % v/v. The diffusion coefficient calculated using this model is $3 \times 10^{-12}$ cm$^2$/s, which is reasonable when compared with available literature data on large and small molecules diffusing into polymers. If one assumes that oil only penetrates from the outer surface of the samples, the calculated diffusion coefficient is unreasonably fast.

Several results from this work have direct implications for the use of cotton-phenolic retainers in oil-lubricated ball bearings. First, retainers must be dry before immersion in oil, or very little oil will be absorbed. Second, changing the cloth weave will not have any great effect on the amount of oil stored in a retainer. (Changing the manufacturer or the required density of the phenolic might affect the stored oil amount.) Third, oils of different viscosities will absorb at different rates, which can be calculated from the model. It is probable that soaking a retainer in oil for only a few hours, as is sometimes done in industry, results in an incompletely filled retainer. Such a retainer may then continue to absorb oil from its bearing during storage, resulting in less than optimal performance.

Saturation of the material with oil occurs only after about two years of storage in a room temperature oil bath. If this diffusion takes place in a stored, lubricated bearing it may affect the availability of oil during later bearing use. For a lightly lubricated bearing where a thin oil film is in contact with the retainer, creep of the oil and absorption into the retainer over long storage times could constitute a serious oil-depletion mechanism.

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